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ORIGINAL RESEARCH

Global Research Status of Maca (*Lepidium Meyenii* Walp.): A Bibliometric Analysis of Hotspots, Bursts, and Trends

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Purpose: This bibliometric study aims to comprehensively analyze the research landscape of Maca (*Lepidium meyenii* Walp.) from 2003 to 2024, identifying key research areas, trends, and patterns, as well as the roles of major countries and institutions in advancing the field.

Methods: A quantitative analysis of literature pertaining to Maca was performed utilizing the bibliometric tools VOSviewer, CiteSpace, and R Bibliometrix. This analysis encompassed an examination of publication frequency, author collaboration networks, and keyword co-occurrence patterns.

Results: The number of published studies on Maca has increased every year since it was studied, with China, Peru, and the United States being the leading countries studied. Research focuses on pharmacology (hormone regulation, antioxidant effects), nutrition (nutrient composition), phytochemistry (bioactive compounds) and agriculture (cultivation techniques). An important feature of Maca research is international collaboration, including researchers from Asia, Europe, South America, and other regions. Keywords such as "maca", "nutritional composition" and "pharmacological action" are particularly prominent. The study of maca polysaccharides has become a focus area, showing potential in various aspects of health such as immunity and anti-tumor effect.

Conclusion: Maca research is growing, with international collaboration crucial. Future research should explore Maca's biological mechanisms deeper, especially those of Maca polysaccharide, and enhance cross-country research comparisons. Our study provides a comprehensive understanding of Maca research trends, guiding further investigations.

Keywords: Maca (*Lepidium meyenii* Walp.), bibliometrics, trends, literature analysis, VOSviewer, CiteSpace, R bibliometrix

Introduction

Maca (Lepidium meyenii), a herbaceous plant native to the Andes mountains in South America, also known as "Peruvian ginseng", is a cruciferous plant indigenous to the high - altitude regions of the Peruvian Andes, growing at elevations between 3700 and 4500 meters and having adapted to extreme environmental conditions, including low temperatures, intense ultraviolet radiation, and arid conditions.[1] Beyond its traditional role as a staple food crop, Maca is particularly valued for its nutrient - rich roots, which have garnered attention both as a nutritional resource and as potential ingredients in traditional medicine and pharmaceutical formulations. In recent years, the cultivation of Maca has been extended to other countries, such as China and India, where the climatic and soil conditions are conducive to its growth. However, despite its ability to thrive in environments beyond its natural habitat, Maca's chemical composition and nutritional value may vary significantly when cultivated in different conditions.[2] The diversity of Maca has promoted its growing utilization, especially in the fields of nutritional supplements and natural food

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products.[3] Maca has a long - standing history of application in traditional practices. It has been used to enhance physical strength, improve reproductive health, and promote overall well - being. In the 20th century, it gradually came to the attention of the international community. Especially in the fields of nutritional supplements and traditional medicines.[4] With the progress of research, scientists have began to examine the chemical composition and pharmacological effects of Maca, confirming the efficacy of its traditional applications. Recent studies have revealed that Maca is a rich source of nutrients, included of dietary fiber, amino acids, fatty acids, and vitamin C, copper, iron, and calcium.[5] It is hypothesized that these components exert an effect on fertility, energy levels and overall health. Additionally, the research revealed the presence of Macamine and Macaene in Maca, Glycerophosphate, Alkaloid, Maca Polysaccharide and Sterol et secondary metabolite.[6–10] International research on Maca is more advanced. It has focused on analyzing its components, pharmacological effects, health benefits, and mechanisms of action. A substantial body of evidence indicates that Maca has the potential to improve reproductive capacity, enhance sexual performance, reduce fatigue, act as an antioxidant, provide neuroprotection, alleviate Menopause Syndrome, and prevent osteoporosis.[11–18] In 1982, the United Nations Food and Agriculture Organization convened an international conference, during which the nutritional value and health benefits of Maca were discussed, and following this conference, the Organization repeatedly recommended that countries cultivate Maca.

In recent years, a growing number of interest in the study of Maca has gradually increased. In order to comprehensively understand existing research and identify new trends, it is necessary to conduct a thorough and systematic review of the literature. To meet this requirement, we employed bibliometric research methods. Bibliometrics is a quantitative methodology that originated in the early 20th century. It employs mathematical and statistical techniques to evaluate and quantify literature within a specific research domain.[19,20] This approach utilizes a range of software tools, each with distinct advantages and limitations. Notable tools include CiteSpace, VOSviewer, HistCite, and BibExcel.[21,22] Among these, VOSviewer, CiteSpace, and R are particularly popular for bibliometric analysis. This approach enabled us to present a detailed account of Maca research literature from January 1, 2003, to August 10, 2024. The following section analyzes research articles on Maca, covering the evolution of the field, prevailing areas of investigation, and emerging research trends.

Materials and Methods

Data Sources

This study selected Web of Science as a data source. Web of Science, a high-quality bibliographic database, is considered by many researchers to be the most suitable database for bibliometric analysis.[23] The original data analyzed in this study was obtained from two databases in Web of Science: Science Citation Index Expanded (SCI-Expanded), and Social Sciences Citation Index (SSCI). The retrieval strategy was as follows: TS= ("MACA") OR ("Lepidium meyenii"). The time span was from January 1, 2003 to August 10, 2024, the language was English, and the document types selected were Articles and Review Articles. The search results after reweighting yielded a total of 804 journal articles (including 726 journal papers and 78 review papers). Further screening of the retrieved papers resulted in 445 valid papers (including 379 journal papers and 66 review papers). Data sources and processing are shown in the Figure 1.

Methodologies

Bibliometrics first appeared at the beginning of the 20th century. By 1969, it had become an independent discipline widely used in bibliometric analysis and bibliometric analysis to provides a quantitative methodology for reviewing and investigating the extant literature in a particular field and the full bibliographic details, including author, keywords, journal, country of publication, institution, and references.[24] Accordingly, the growth of a given field can be gauged through bibliometric analysis. Modern computer technology allows for the incorporation of graphical and visual results, which could be employed to supplement the analysis of literature. In the field of bibliometric analysis, the concept of co-citation is widely utilized. When both articles are cited alongside one or more other articles, this relationship is defined as a co-citation relationship (visual analysis). It should be noted that bibliometric co-citation analysis visualization

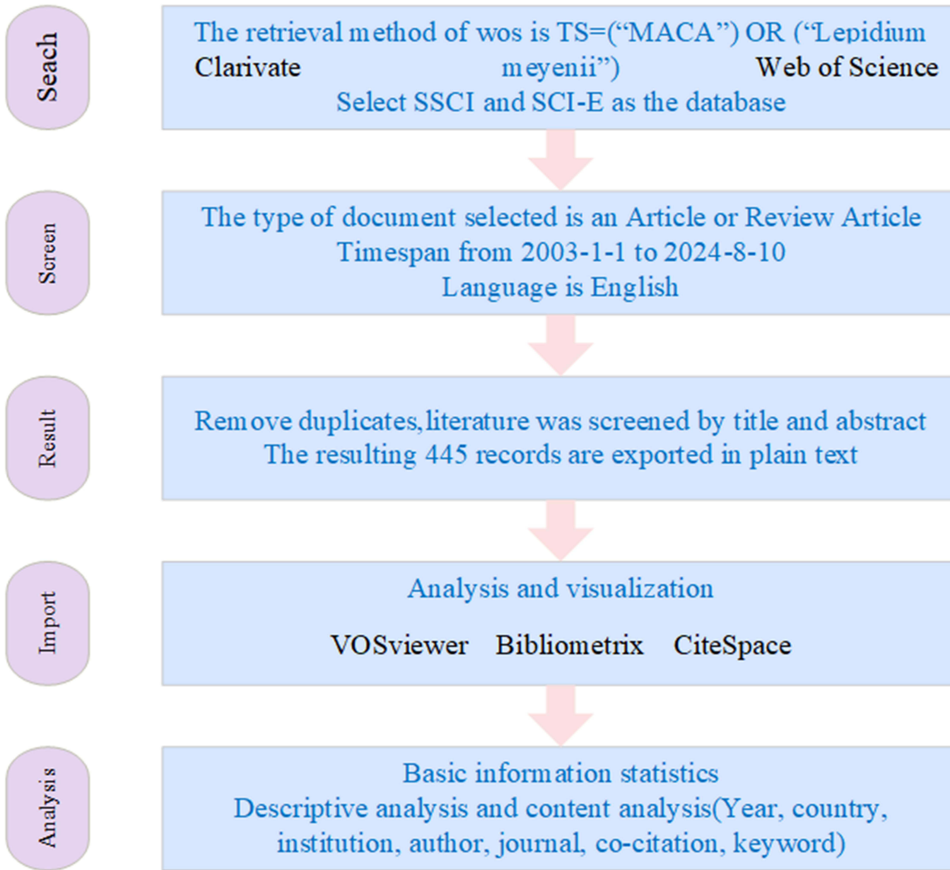

Figure 1 Maca research data collection and analysis flowchart.

methodology helps data comprehension and increases the comprehensiveness of the outcomes. Moreover, in addition to the article itself, most of the elements included in the article, such as the author, keywords, institutions, and countries, can be accessed and utilized through this method. The visualization of information aids in the discovery of intrinsic connections between disparate data sets. For instance, it facilitates the identification of shared research themes among different authors, the mapping of research priorities across diverse institutions, and the tracing of new theoretical insights emerging from existing research organizations. In this study, VOSviewer, CiteSpace and R Bibliometrix were used as analytical tools to to analyze the current research status of maca. VOSviewer, also known as the Visualization of Similarities Viewer, is a free and open-source software developed by the team at the University of Leeds. It is primarily utilized by researchers to facilitate the analysis, visualization, and comprehension of various forms of academic data, including bibliometric and network analysis.[25] CiteSpace is a tool for visualizing and analyzing the network of scientific literature. It was developed by Chen Chaomei, a professor at the University of Delaware's School of Information and Technology, in collaboration with the WISE Laboratory at Dalian University of Technology. The tool aims to assist researchers in exploring and comprehending the structure and evolution of academic fields. It is primarily used to conduct a quantitative analysis of specific subject areas in order to present the structure and evolution of research within a given field of study.[26] Bibliometrix is a software program developed by Massimo Aria and others professors of economics and statistics at the University of Naples Federico II. It is a scientific literature analysis and visualization tool based on the R language that offers numerous advantages in the areas of bibliometric analysis, index calculation, network analysis, and knowledge mapping. It supports the importation of data from the Web of Science or other databases, while providing access to a rich set of computational and visualization libraries. It is open-source and can be used for free.[27] R Bibliometrix was used for the discovery of fundamental quantitative information pertaining to literature, the analysis of research institutions, and the visualization of keywords. VOSviewer as a visualization tool to enables the exploration of author collaboration, national collaboration, and joint authorship across knowledge domains. CiteSpace was used for the generation of overlay and burst graphs.

Results

The Following Is a Statistical Overview of the Data

This study analyzed 445 articles authored by 2016 researchers from 651 institutions across 57 countries. These articles were published in 221 journals and cited 15,713 articles from 4913 different journals.

A Yearly Analysis of the Publication Trends

A totals of 445 articles on Maca was search of the Web of Science core collection. Following the screening process, 379 research articles and 66 review articles were identified. The primary focus of these studies was on isolating a single compound from Maca, analyzing its chemical composition, and conducting botanical research. Figure 2 illustrates the temporal distribution of publications in the Maca research field. A review of Maca-related literature published between 2003 and 2024 reveals a consistent upward trajectory in the cumulative number of articles, which can be delineated into three distinct phases. In the initial phase (2003–2013) the number of annual publications was below 100. In the second phase (2014–2020), the number of published articles per year was less than 300, indicating an advancement in Maca research. The third phase, commencing in 2021, saw the number of annual publications exceed 300. A comprehensive analysis of the data reveals a notable increase in the volume of publications in this field, particularly following 2016. In 2021 and 2022, the number of publications rapidly increased and reached its peak. The cumulative publication curve aligns with a second-order polynomial curve, demonstrating a superior fit (R^2=0.9929). This suggests that the future growth rate of research output in this field will be higher. This observation indicates that Maca has garnered significant attention from researchers in recent years.

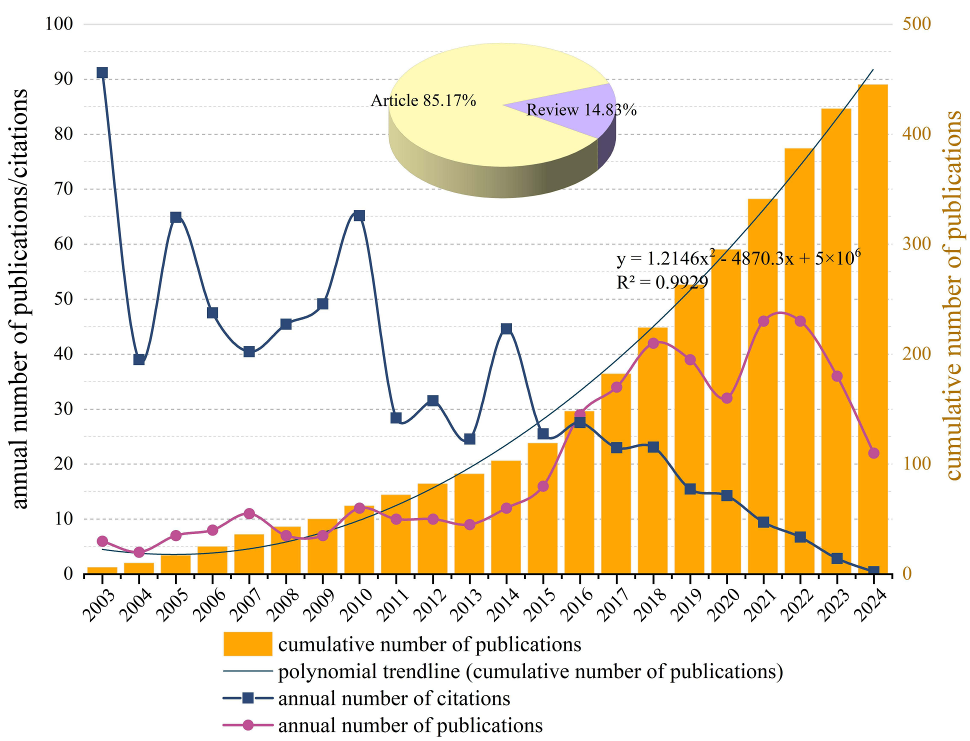

Figure 2 The bar chart shows the number of annual publications related to Maca from 2003 to 2024. The line graph illustrates the annual publication and citation. The pie chart represents the relationship between the article and the review.

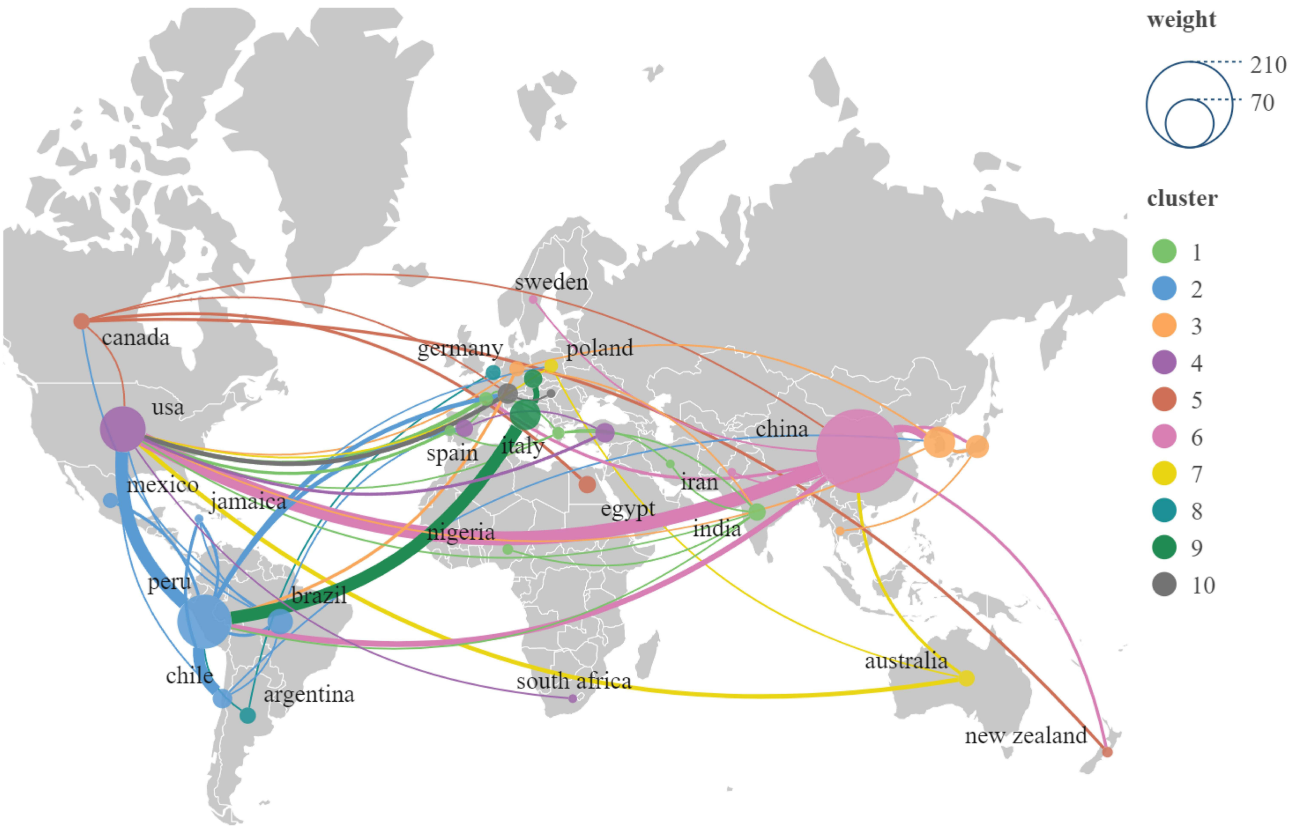

Figure 3 Country/ regional analysis of Maca's field of study.

Analysis of Research Countries

Figure 3 presents the geographical distribution of countries where research on Maca has been published. China, Peru, and the United States emerge as the leading contributors to Maca-related academic literature (Table 1). Among the 57 countries publishing Maca research, China at the forefront with 185 articles. Peru follows with 77 articles, trail with the United States and South Korea with 55 and 26 articles, respectively. Articles related to Maca from China garnered a total of 3352 citations, rendering it the most frequently cited country in this domain. Peru occupies the second position, with a total of 2017 citations. As illustrated in the diagram, the greater the strength of the link, the thicker the line between the two countries, proportional to the strength of their collaborative ties. Thus, it can be inferred that Peru (Total Strength) established particularly robust collaborative relationships with other countries. In addition, the United States demonstrates the most extensive cooperation with other nations, with a total of 14 links.

Table 1 Top 10 Countries in Terms of Publications

Rank	Countries	Continent	Documents	Citations
1	Peoples R China	Asian	185	3380
2	Peru	South America	77	2017
3	USA	North America	55	1876
4	South Korea	Asian	26	829
5	Italy	Asian	25	423
6	Brazil	South America	17	266
7	England	European	15	358
8	Japan	Asian	14	186
9	Switzerland	European	11	346
10	Chile	South America	10	516

The research findings indicate that regions with significant Maca production demonstrate heightened research engagement and investment in this field. This geographical concentration of research activities reflects both the prioritization of maca studies by local scientific institutions and contributes to the sustainable development of maca-related industries. Furthermore, this research-industry synergy facilitates the optimization of regional industrial structures and accelerates the translation of scientific findings into practical applications.

Analysis by Research Institutions

Table 2 lists the top ten organizations in terms of their contributions to Maca research. Figure 4 provides a detailed analysis of research institutions worldwide, highlighting key contributors in the field. The Universidad Peruana Cayetano Heredia at the forefront with 41 publications. The Chinese Academy of Sciences (CAS) follows closely with 32 publications. In third place, Jiangnan University and the National University of San Marcos each having published 15 articles. Notably the two institutions with the most publications demonstrate a particularly strong collaborative partnership.

In the research field of Maca, institutions are mainly composed of universities, hospitals and research institutes, and the research focus of each team is also different. The research content ranges from basic research (effective ingredients, preparation compatibility, in vivo process, mechanism of action, pharmacodynamic evaluation) to clinical research (safety evaluation, clinical evaluation), and scholars are not systematic in all directions. The research is scattered and insufficient in depth.

Analysis of Study Authors

Lotka's Law, introduced by American statistician Lotka in 1926, describes the empirical relationship governing scientific productivity.[28] In 1963, scholar Price highlighted that in a given field, half of the total publications are authored by a small group of highly productive individuals, with the number of these authors approximately equal to the square root of the total number of authors:[29]

$$\sum_{m+1}^{\mathrm{I}} n(x) = \sqrt{\mathrm{N}}$$

In this context, the function n(x) represents the number of authors who have published x articles. The value I is defined as the maximum number of articles published by any single author in this field, which has been determined to be 11 articles through statistical analysis using the VOSviewer software. The variable N represents the total number of authors, while the parameter m denotes the minimum number of articles published by a single author. In accordance with Price's Law, the minimum number of publications required from a core author in a specific field m=0. $749\times\sqrt{n\max}$ ≈2. 48. Accordingly, authors who have published more than two articles are identified as core authors in this domain. A total of 107 core authors have published 474 articles collectively. This figure meets

Table 2 Top 10 Maca Research Organizations

Rank	Institutions	Countries	Documents	Citations
1	Univ Peruana Cayetano Heredia	Peru	41	1402
2	Chinese Acad Sci	Peoples R China	32	614
3	Jiangnan Univ	Peoples R China	15	280
4	Univ Nacl Mayor San Marcos	Peru	15	205
5	Huazhong Univ Sci & Technol	Peoples R China	14	374
6	Univ Chinese Acad Sci	Peoples R China	14	264
7	Yunnan Acad Agr Sci	Peoples R China	13	130
8	Minist Educ	Britain	12	235
9	South China Univ Technol	Peoples R China	9	313
10	Yunnan Minzu Univ	Peoples R China	9	85

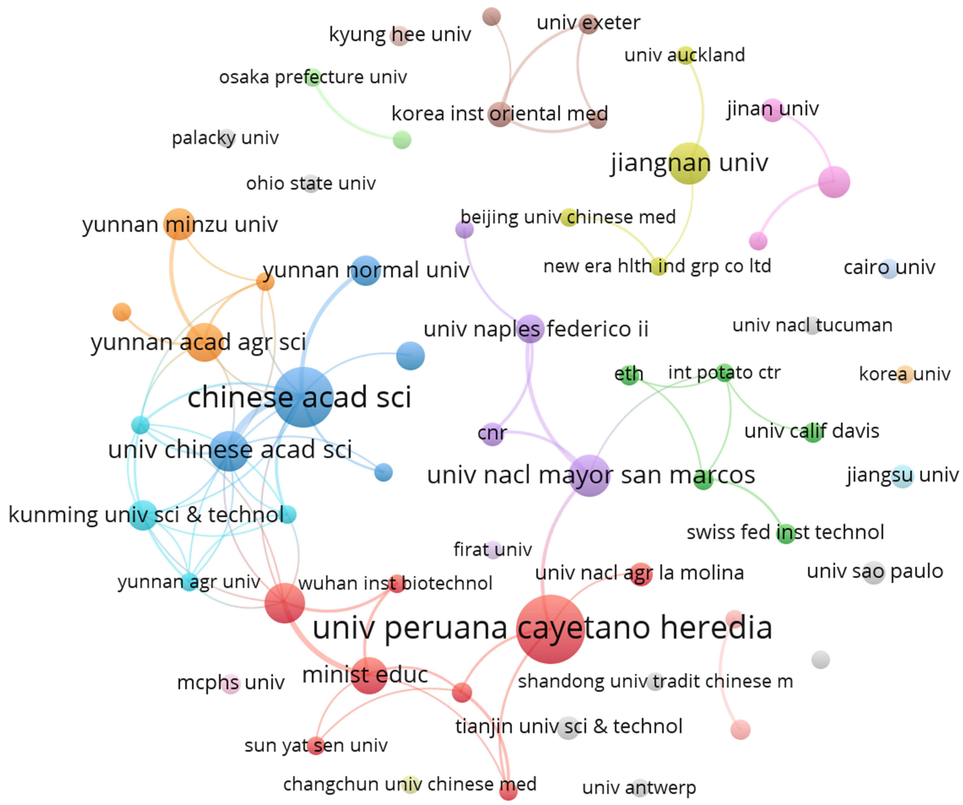

Figure 4 An institutional analysis of the Maca's field of study.

the 50% threshold proposed by Price and aligns closely with the calculations derived from Price's Law. It can be inferred that a relatively stable collective of authors has emerged within the field of Maca research.

Table 3 highlights the most prolific authors in this field, defined as those with a publication output exceeding eight articles. Figure 5B depicts the temporal trends of the annual publication output of the top ten authors. Gustavo F. Gonzales is the author with the highest number of published articles, first publishing his work in 2003. Since then, he has authored a total of 35 articles, which garnered 1367 times. The second-highest ranking author is Manuel Gasco, who published his first article also in 2003. Gasco has published a total of 21 articles, which have been cited 870 times, and has frequently collaborated with Gonzales. The temporal distribution of publications reveals a decline in output from both Gonzales and Gasco beginning in 2014, with no further contributions to the field of Maca studies until 2020. During this period, several authors from China continued to produce research in this domain.

Table 3 Top 10 Authors and Co-Cited Authors Related to Maca Research Area

Rank	Author	Documents	Citations	Average Citation/ Publications
1	Gonzales, Gustavo F.	35	1367	39. 06
2	Gasco, Manuel	21	870	41. 43
3	Jin, Wenwen	11	225	20. 45
4	Yu, Longjiang	10	193	19. 30
5	Wu, Hui	8	419	52. 38
6	Zhang, Mengmeng	7	324	46.29
7	Zhao, Bing	7	259	37.00
8	Zhou, Min	7	83	11.86
9	Carotenuto, Domenico	6	73	12.17
10	Ciani, Francesca	6	73	12.17

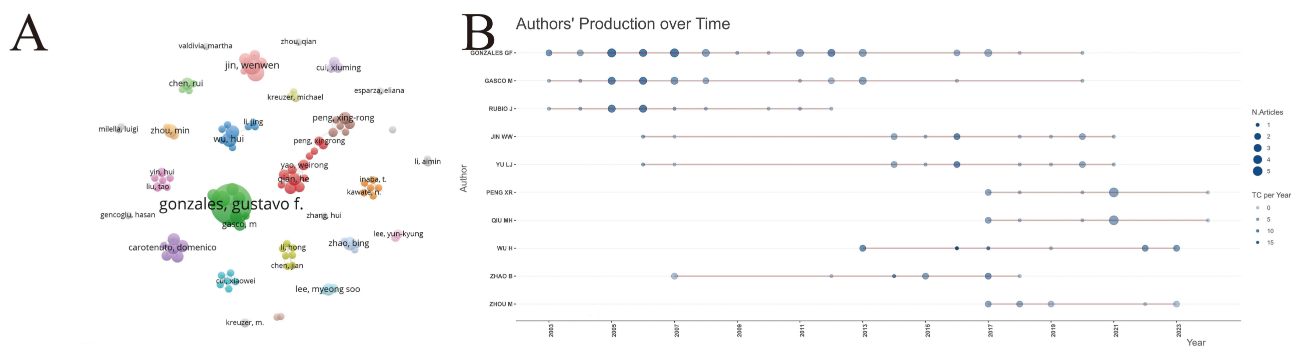

Figure 5 The author's contributions to the field of maca research. (**A**) Network diagram of collaborative partnerships of authors in the field of maca research. (**B**) Timeline plot of the number of articles and citations for the top 10 most productive authors. Node size indicates the number of articles published, and node color depth indicates the number of citations.

The collaborative network analysis depicted in Figure 5A reveals the intellectual contributions and interconnections among authors actively contributing to Maca research. This visualization not only facilitates the identification of emerging collaborative clusters but also quantifies the extent of scholarly synergy within the field. The network comprises 27 distinct clusters, with node density and edge thickness reflecting collaboration intensity. Notably, the largest consortium, led by Peng Xingrong and Qian He, is composed of 17 researchers who have collectively authored 75 peer-reviewed articles, demonstrating significant thematic cohesion and productivity.

Journal Analysis

As a core objective of bibliometric inquiry, this study employs statistical methodologies to map journal distribution patterns and evaluate their disciplinary alignment with Maca research. Such analysis provides critical guidance for researchers in identifying target journals that optimally match their work's scope and impact potential. Our findings reveal a concentrated publication landscape, where the top 10 journals (Table 4) collectively account for 14.8% of all Maca-related publications. Geographically, these journals are distributed across six nations: the United Kingdom, the Netherlands, the United States, Switzerland, Germany, and Ireland. *Andrologia* emerges as the dominant contributor with 19 publications (395 citations), while *Evidence-Based Complementary and Alternative Medicine* demonstrates exceptional scholarly influence, achieving the highest citation-per-article ratio (67.71) despite fewer total publications.

Figure 6 synthesizes bibliometric maps with empirical data, visually delineating the disciplinary focus of journals engaged in Maca research. A clear dichotomy emerges: Cited journals predominantly represent domains such as toxicology, nutrition, and clinical chemistry, whereas publishing journals cluster in molecular biology, immunology, and translational medicine. This divergence likely reflects the dual nature of Maca research — mechanistic investigations

Table 4 The Top 10 Most Published Journals and the Top 10 Most Cited Co-Cited Journals in Maca Research

Rank	Source	Publications	Citations	Average Citation/ Publications
1	Andrologia	19	395	20. 79
2	International Journal Of Biological Macromolecules	16	520	32. 50
3	Journal Of Ethnopharmacology	13	469	36. 08
4	Food & Function	10	321	32. 10
5	Molecules	10	89	8. 90
6	Food Chemistry	8	277	34. 63
7	Phytochemistry Letters	8	128	16. 00
8	Evidence-based Complementary And Alternative Medicine	7	474	67. 71
9	Journal Of Agricultural And Food Chemistry	7	107	15. 29
10	Phytotherapy Research	7	208	29. 71

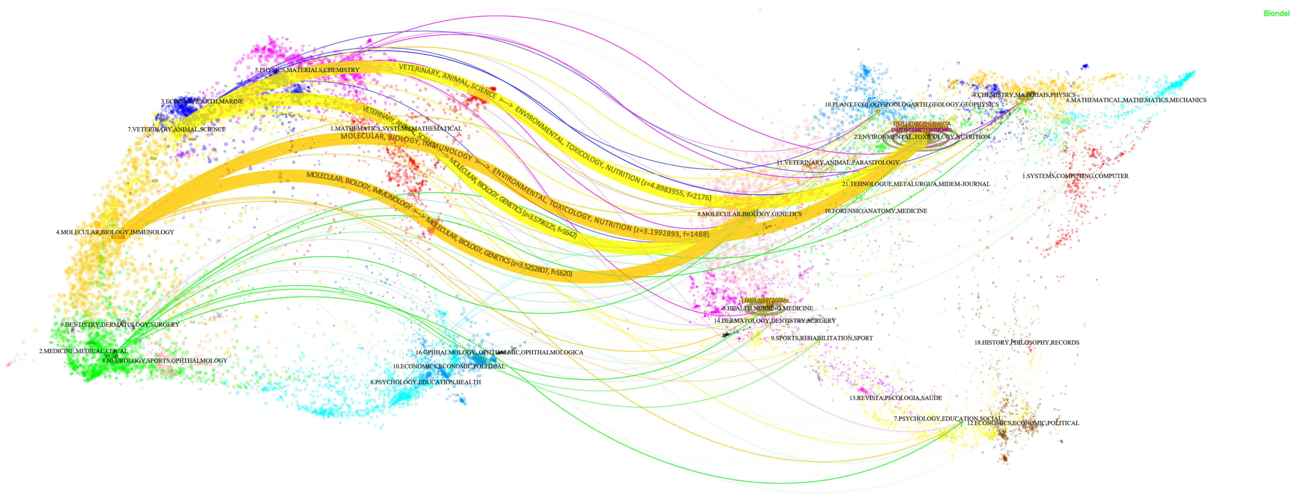

Figure 6 A biplot overlay of journals in the maca research area. The width of the horizontal axis of the ellipse indicates the number of authors in the journal, and the length of the vertical axis of the ellipse indicates the number of papers published by the journal.

into bioactive constituents (eg, macamides, polysaccharides) predominantly appear in discipline-specific journals, while applied pharmacological studies align with broader biomedical outlets.

Co-Citation Analysis

The analysis of journals cited is depicted in Figure 7. Each circle in the diagram represents a journal, with the size of the circle proportional to the number of citations that journal has received. The thickness of the connecting lines indicates the frequency with which journals are cited together. Nodes of identical color belong to the same cluster, as shown in the diagram. The three most-cited journals are the *Journal of Ethnopharmacology* (cited 767 times), *Food Chemistry* (cited 577 times), and the *Journal of Agricultura*l and *Food Chemistry* (cited 559 times). All three are classified as JCR Q1 journals. A total of 43 journals were identified as having been cited 75 times or more. The red cluster primarily addresses the pharmacological and toxicological aspects of Maca, as well as the chemical composition of drugs. The green cluster focuses on the use of Maca in food products. In contrast, the blue cluster is dedicated to the botanical aspects of Maca.

To gain a deeper understanding of citation patterns within the domain of Maca knowledge, VOSviewer software was utilized to construct a bibliometric network map (Figure 8), illustrating source co-citation relationships. Applying a threshold of at least 50 citations, a total of 21 articles were identified for inclusion in this study. These selected works underwent co-citation analysis, culminating in the development of a comprehensive co-citation network. Moreover, the five most frequently cited articles are summarized in Table 5. The resultant citation relationship map delineates that can be systematically categorized into two distinct clusters. The green cluster represents "Effect of a lipidic extract from *Lepidium meyenii* on sexual behavior in mice and rats" a more systematic investigation was conducted to ascertain the efficacy of Maca extract on sexual behavior in rats of both species.[30] "Effect of Lepidium meyenii (Maca), a root with aphrodisiac and fertility-enhancing properties, on serum reproductive hormone levels in adult healthy men" a 12-week, double-blind, placebo-controlled, randomized, parallel-group trial was conducted to assess the impact of varying doses of Maca Gelatinizada on serum reproductive hormones and sexual function.[31] "Investigation of the tuber constituents of maca (*Lepidium meyenii* Walp.)". The phytochemical profile of maca tubers was systematically characterized, with several key constituents identified, including uridine, malic acid, and its benzoyl derivative. A comprehensive analysis revealed the presence of glucosinolates, specifically glucotropaeolin and m-methoxyglucotropaeolin, along with decomposition products derived from thiodiguanosine. Isothiocyanic acid and its methyl ether derivatives were successfully isolated through chromatographic techniques. Significantly, (1R,3S)-1-methyltetrahydro-β-carboline-3-carboxylic acid was detected for the first time in this species, suggesting potential biosynthetic implications in secondary metabolite production.[32] In the red cluster, "aca: An Andean crop with multi-pharmacological functions" the primary objective was to conduct a comprehensive review of the chemical composition

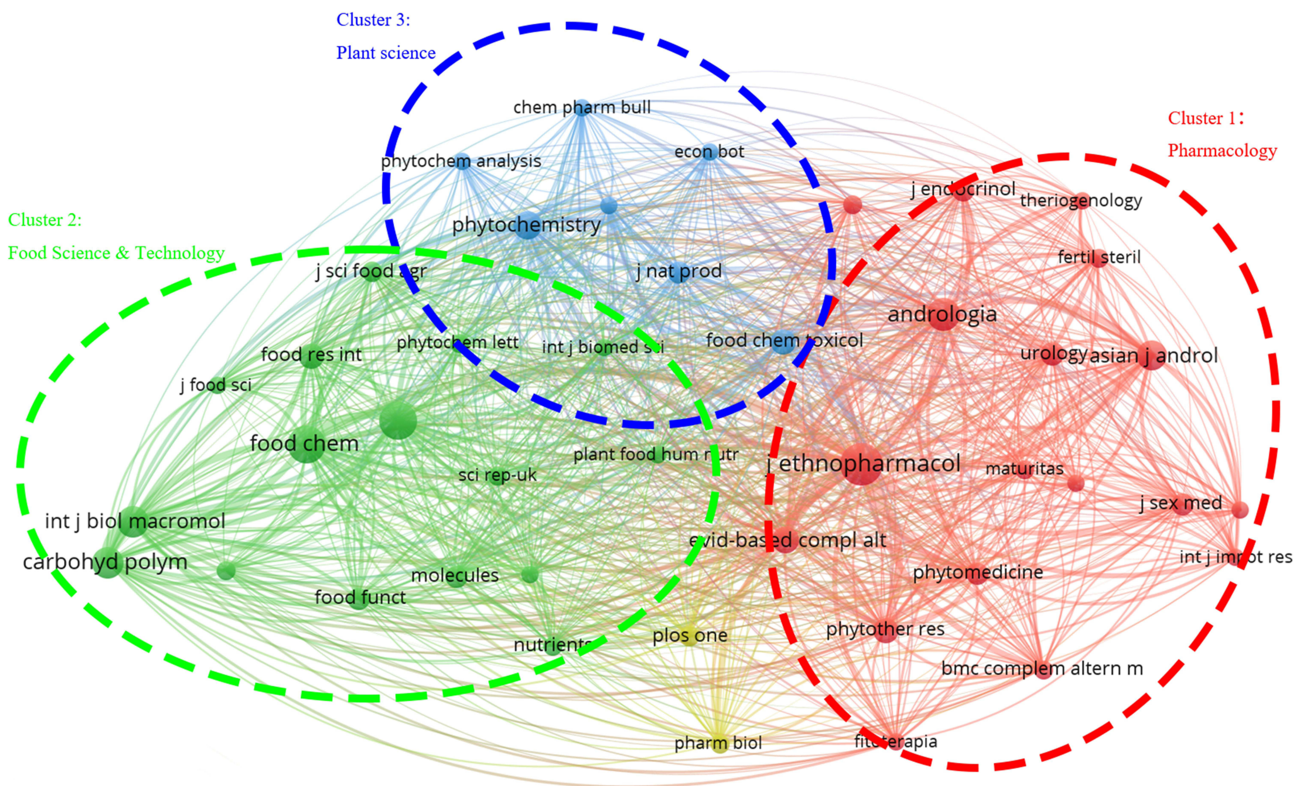

Figure 7 Knowledge domain mapping of journal co-citations for maca-related research. The size of the nodes indicates the frequency of journal citations in articles on licorice research; the color of the nodes indicates the type of cluster; the line connecting the two journals indicates that the two journals were cited in the same publication, and the thickness of the line reflects the frequency of co-citations between the two journals.

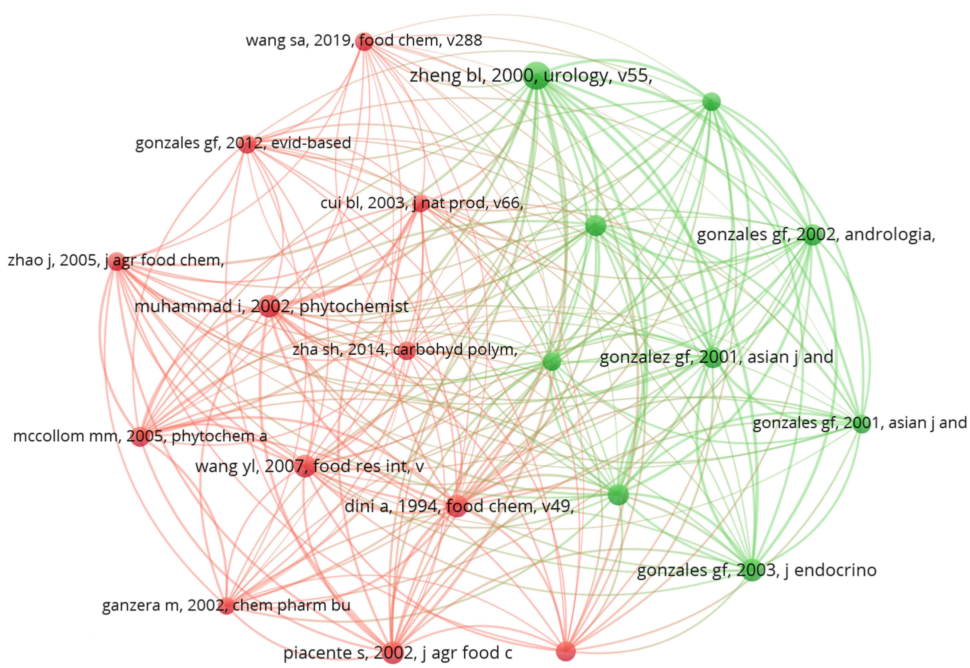

Figure 8 The co-citation relationship graph shows the mapped knowledge domain of co-cited references for maca-related studies. Node size indicates the number of references cited in maca research articles; node color indicates different cluster types; and the thickness of the connecting line indicates the co-citation rate between two cited references.

Table 5 Top 10 Most Cited Co-Cited Journals in Maca Studies

Rank	Title	Journal	First author	Year	Citations	Ref.
1	Effect of a lipidic extract from *Lepidium meyenii* on sexual behavior in mice and rats	Urology	Zheng BI	2000	125	[30]
2	Chemical composition of *Lepidium meyenii*	Food Chem	Dini A	1994	84	[34]
3	Effect of *Lepidium meyenii* (Maca), a root with aphrodisiac and fertility-enhancing properties, on serum reproductive hormone levels in adult healthy men	J Endocrinol	Gonzales Gf	2003	83	[31]
4	Investigation of the tuber constituents of maca (*Lepidium meyenii* Walp.)	J Agr Food Chem	Piacente S	2002	82	[32]
5	Constituents of *Lepidium meyenii* "maca"	Phytochemistry	Muhammad I	2002	81	[35]
6	True corrected seminal fructose level: a better marker of the function of seminal vesicles in infertile men	Asian J Androl	Gonzalez GF	2001	79	[36]
7	*Lepidium meyenii* Walp. improves sexual behaviour in male rats independently from its action on spontaneous locomotor activity	J Ethnopharmacol	Cicero AFG	2001	78	[37]
8	Effect of *Lepidium meyenii* (MACA) on sexual desire and its absent relationship with serum testosterone levels in adult healthy men	Andrologia	Gonzales GF	2002	77	[38]
9	Effect of short-term and long-term treatments with three ecotypes of *Lepidium meyenii* (MACA) on spermatogenesis in rats	J Ethnopharmacol	Gonzales C	2006	73	[39]
10	Analysis of macamides in samples of Maca (*Lepidium meyenii*) by HPLC-UV-MS/MS	Phytochem Analysis	McCollom MM	2005	68	[40]

and pharmacological actions of Maca.[33] "Chemical composition of Lepidium meyenii" a comparative analysis was conducted to evaluate the nutritional composition of Maca against that of potatoes and carrots, aiming to determine Maca's potential as a food source.[34]

Keyword Hotspot Analysis

Keywords extracted from scholarly literature serve as critical indicators for identifying research domains and thematic priorities. Through quantitative analysis of high-frequency terminology across related studies, researchers may discern core research foci and emerging trends within the field. A bibliometric analysis was performed on keyword occurrences in maca-related literature, with results visualized as a treemap (Figure 9B) where keyword dimensions proportionally represent frequency metrics. As delineated in the visualization, the predominant keywords emerged as "extract" (n=81, 13%), "sexual-behavior" (n=50, 8%), and "constituents" (n=48, 8%), collectively accounting for 29% of total keyword occurrences.

Co-occurrence analysis of the 60 most frequent keywords in Maca literature yielded four discrete clusters (60 nodes total), as visualized in Figure 9A and quantified in Table 6. The red cluster ("extract") predominantly encompasses sexual behavior investigations, while the green cluster delineates pharmacodynamic properties, particularly spermatogenesis modulation and polysaccharide bioactivity. Blue cluster constituents focus on macamide phytochemistry, whereas the yellow cluster specifically addresses oxidative stress models in murine systems (Rattus/Mus). This multivariate analysis reveals Maca's dual pharmacotoxicological profile in stress-related paradigms.

Figure 9C displays a strategic diagram with centrality (x-axis: interdisciplinary influence) and density (y-axis: thematic cohesion) defining four quadrants. Motor themes (high centrality/density) contain "double-blind" and "extract", indicating field maturity and developmental potential. Niche themes (low centrality/high density) feature physicochemical properties and endocannabinoid interactions, demonstrating specialized focus with limited cross-domain integration. Emerging/declining themes (low centrality/density) include root phytochemistry and macamide biosynthesis, necessitating longitudinal investigation to ascertain trajectory. Basic themes (high centrality/low density) comprise antioxidant mechanisms and constituent profiling, representing foundational yet underdeveloped research pillars.

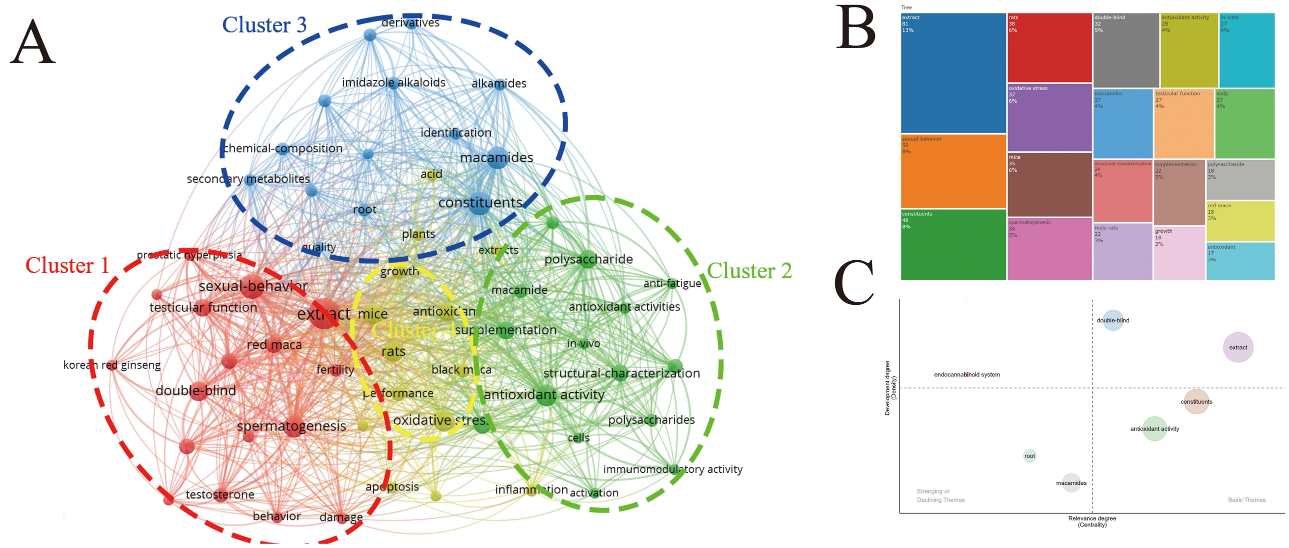

Figure 9 (**A**) Keyword co-occurrence graph for the literature of Maca. The size of the dots indicates the number of keyword occurrences and the color indicates the type of clustering. (**B**) The top 20 most frequent keywords. (**C**) Strategic diagram of theme. Classification and visualization of density and centrality-based topic clustering.

Analysis of Keyword Heat Over Time

Burst detection analysis identifies temporally significant keywords characterized by abrupt frequency increases within defined periods, reflecting evolving research priorities. Temporal boundaries of burst phenomena are demarcated by "Begin" and "End" markers, with "strength" quantifying burst magnitude (higher values indicating greater thematic impact). Preprocessing excluded search-related terms ("MACA" and Lepidium meyenii) via prominence filtering prior to selecting the ten most salient burst terms (Figure 10A). The inaugural burst term "black maca" (1999–2005) signifies early cultivar-specific investigations, while sustained interest in general maca research is evidenced by the prolonged burst duration of "maca" (2007–2016). Contemporary research fronts (2017–present) are dominated by "maca polysaccharide", with emerging focus on "anti-inflammatory activity" demonstrating progressive adoption since 2018. Conversely, declining burst trajectories characterize "food supplement" and "cytotoxic activity", suggesting shifting investigative priorities. Multidimensional evaluation positions "maca polysaccharide" as the predominant research frontier based on both chronological persistence (2017–2023) and maximal burst intensity.

The evolution of research on Maca can be delineated through the analysis of keywords and their frequency distribution over time. Figure 10B–C illustrates that the keywords most closely associated with Maca exhibit distinct patterns of frequency across various time intervals, both in terms of ranking and temporal changes. The subsequent section will delve into this topic in greater detail. In 2024, the term "antioxidant" emerged as a prominent research topic. Maca fermentation leads to a significant increase in several bioactive compounds, including left-handed betaine, macamides, total flavonoids, and total phenolics. The antioxidant and α-glucosidase inhibitory effects of fermented Maca are more pronounced compared to non-fermented Maca. Additionally, Maca shows a 23% enhancement in its neuroprotective efficacy against HT-22 cells.[41] In recent years, infertility has emerged as a prominent topic of interest. Research by Mai H. Mekkawy et al has highlighted the protective efficacy of Maca against radiation-induced oxidative stress. Their study demonstrates that Maca exerts anti-apoptotic and anti-oxidative effects through the GRP78/ CHOP/ caspase-3 pathway. Consequently, Maca helps prevent testicular damage.[42]

Table 6 The Top 10 Keywords in the 4 Clusters

Cluster 1	Occurrences	Total Link Strength	Cluster 2	Occurrences	Total Link Strength	Cluster 3	Occurrences	Total Link Strength	Cluster 4	Occurrences	Total Link Strength
Extract	82	317	Antioxidant activity	39	144	Constituents	49	184	Oxidative stress	39	124
Sexual-behavior	50	218	Polysaccharide	30	131	Macamides	45	163	Rats	38	147
Spermatogenesis	40	159	In-vitro	27	93	Derivatives	15	33	Mice	37	154
Double-blind	32	89	Supplementation	26	119	Imidazole alkaloids	15	61	Antioxidant	28	82
Testicular function	27	124	Structural-characterization	24	98	Root	15	41	Growth	20	49
Red maca	25	109	Purification	20	77	Structural elucidation	15	49	Performance	18	72
Erectile dysfunction	23	60	Macamide	17	48	Brassicaceae	14	42	Black maca	17	70
Male rats	22	104	Endurance capacity	15	65	Chemical-composition	14	38	Acid	12	33
Testosterone	20	70	Polysaccharides	15	44	Alkamides	13	67	Apoptosis	12	39
Fertility	14	56	Antioxidant activities	12	51	Identification	13	42	Inflammation	12	36

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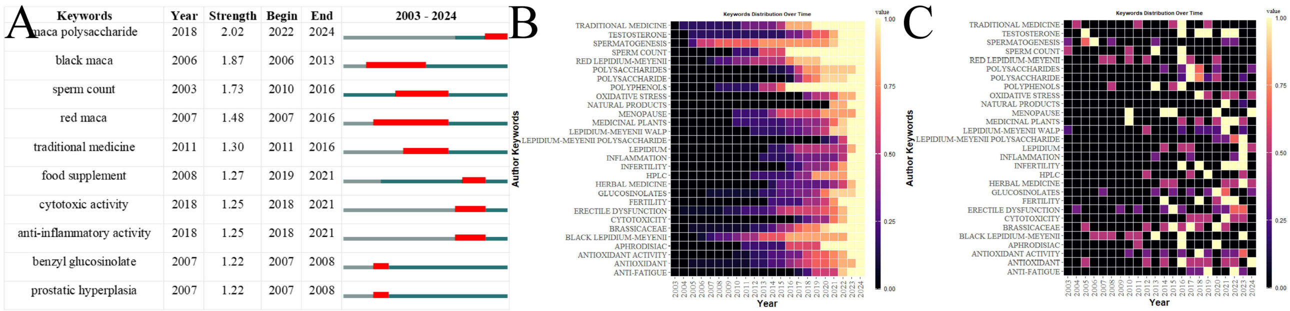

Figure 10 Visual analysis of keyword changes over time. (**A**) Top 10 keywords citing the strongest outbreaks. Sorted by year of outbreak initiation. The red line represents the year of outbreak detection. The red line extends to the most recent year for keywords that may be predictive of future research hotspots in a short period of time. (**B**) Cumulative number of keyword occurrences over time. (**C**) Annual number of occurrences of the top 25 keywords.

Discussion

In recent years, public interest in the study of Maca has significantly increased, particularly during the second phase of research (2014–2020). This period saw a pronounced surge in growth, as illustrated in the accompanying chart. To investigate the development of Maca research from 2003 to 2024, three leading software programs for bibliometric analysis were employed: VOSviewer, CiteSpace, and R Bibliometrix. The results indicate a steady increase in the volume of publications within the field, suggesting a growing interest among researchers in this subject.

Analysis of national collaboration networks suggests promising prospects for expanded global research and applications of maca. While certain research teams have emerged through author and institutional partnerships, particularly among universities and research institutes, the overall scope of collaboration remains limited. The relatively sparse connections between existing teams indicate a need to strengthen cross-regional and interdisciplinary academic exchanges to establish more comprehensive collaborative relationships in maca research. A review of national research findings indicates that China has the highest output of Maca. The majority of Maca produced in China is sourced from regions with high altitudes, including Yunnan and Tibet. The research encompasses the starch properties of Maca from various forms,[43] a study of the extraction and biological activity of Maca triterpenoid,[44] a novel compound identified in Maca and its biological activity,[45] the impact of maca root on the external digestive and immune systems,[46] the relationship between maca, a natural alkaloid and phenol, and antioxidant activity.[47] Additionally, Chinese scholars have investigated the properties of Maca as they are described in traditional Chinese medicine,[48] the objective is to investigate the interaction between Maca and traditional Chinese medicine. For instance, the combination of maca and fenugreek has been shown to enhance the content of maca alkaloids, thereby improving the efficacy of maca in treating male sexual dysfunction when used in conjunction with a single pharmacological agent.[49] Despite the current evidence indicating that the combination of different drugs holds promise,[50] Nevertheless, further clinical trials and fundamental research are required to confirm the specific mechanisms by which these effects are produced. Furthermore, future Maca research will focus on investigating the effects of varying doses and combinations.[51]

In terms of relevant literature authors and publishing institutions, the analysis results show that although deeper cooperation groups have not yet formed, several large research groups have initially formed, and universities are the main force of publishing papers and participate in more related studies. The Universidad Peruana Cayetano Heredia, a preeminent academic institution in Peru, stands at the forefront of Maca research, boasting the highest number of publications in this domain. Research conducted at this university primarily centers on endocrinology, while also spanning a diverse array of disciplines, including metabolism, integrative and complementary medicine, toxicology, urology, nephrology, and plant sciences. A recent study from this institution investigates the impact of temperature, genotype, and germination promoters on the germination and early growth of Maca seeds.[52] The most-cited article from this institution, as indicated by Web of Science, explores the potential of Maca dietary supplements to enhance male reproductive health, specifically sperm production and quality.[53] Another frequently cited review offers the most comprehensive account of Maca's ethnobiological and ethnopharmacological aspects.[4]

The analysis of keywords and the visualization of their popularity over time reveal that current research on Maca is concentrated in several key fields, including pharmacy, pharmacology, molecular biology, chemistry, plant science, and immunology. The primary focus of these studies centers on the biological activity of secondary metabolites extracted from Maca, which encompass Maca acid, Maca alkaloid, and Maca polysaccharide.

Macamides have been a focal point in maca research for some time. Researchers are currently investigating the biosynthetic pathways of macamides,[54] isolating new compounds,[55,56] and exploring their mechanisms of action. Macamides are a unique class of amide alkaloids found exclusively in maca, with over 30 types identified to date.[57] These compounds are considered the functional components of maca. One of the most notable effects of macamides is on the reproductive system, with studies indicating efficacy in both males and females.[58] Research on the impact of macamides on gut microbiota has shown that they regulate the L-glutamate-ornithine-proline axis by breaking down histidine, arginine, and proline, thereby alleviating exercise-induced skeletal muscle fatigue in mice.[59] Among the macamide family, N-benzyl-hexadecanamide (NBH) enhances endurance in mice by increasing liver glycogen levels and reducing blood urea nitrogen, lactate dehydrogenase, blood ammonia, and blood lactate levels.[60,61] Additionally, N-benzyl-linoleamide has been found to reduce lipopolysaccharide-induced inflammatory pain by inhibiting epoxide hydrolase.[62] These studies collectively indicate that significant progress has been made in understanding macamides. Currently, the structure-activity relationship of macamides remains understudied, necessitating further investigation into their efficacy, structural properties, and structure-activity correlations. Future research directions should prioritize several key aspects: first, the optimization of industrial-scale synthesis and production conditions for macamides; second, the elucidation of molecular mechanisms underlying their biological effects, particularly regarding anti-fatigue properties, reproductive benefits, and gut microbiota modulation; and third, comprehensive evaluation of their pharmacological effects through rigorous clinical trials to establish evidence-based therapeutic applications.

Maca polysaccharides have recently emerged as a prominent research focus in phytochemistry and pharmacology. As natural polymers composed of over 10 monosaccharides, plant polysaccharides are widely distributed in plant tissues and recognized for their multifaceted biological activities. Pharmacologically, maca polysaccharides demonstrate cardioprotective effects, antitumor potential through malignant cell growth inhibition, antioxidant capabilities via oxidation process suppression, intestinal microbiota regulation, antibacterial properties, and utility as medicinal adjuvants.[63–69] Maca polysaccharide, extracted from the maca root, is primarily composed of heteropolysaccharides, which are influenced by both the source material and the purification process used. Studies have shown that this polysaccharide typically consists of multiple distinct monosaccharides, such as glucose, arabinose, galactose, and rhamnose.[70] The biological activity of polysaccharides is significantly influenced by the proportion and sequence of their monosaccharides. Additionally, the molecular weight of maca polysaccharides is another critical structural characteristic. Techniques such as high-performance liquid chromatography (HPLC) and high-performance gel permeation chromatography (HPGPC) can be employed to determine the molecular weight of maca root extract.[71] Research shows that Maca polysaccharide has a broad molecular weight distribution, which may affect its biological activity.[72] The linkage of Maca polyphenolic compounds is also a defining structural feature.[72] Research shows that maca root extract significantly reduces fatigue by improving energy metabolism, thereby enhancing endurance and physical capacity.[73] Maca polysaccharide exhibits significant antioxidant properties, which protect cells from oxidative damage by neutralizing intracellular free radicals.[74] This antioxidant effect not only decelerates the aging process but also potentially lowers the risk of chronic diseases such as cardiovascular disease and cancer. Recent studies have shown that maca root extract significantly enhances the activity of antioxidant enzymes, thereby bolstering the body's natural defenses. Additionally, maca polysaccharide plays a crucial role in immune regulation by increasing the levels of IFN-γ, TNF-α, and IL-2, while reducing IL-4 levels,[75] thus influencing cytokine production. This immune-modulating capability positions Maca polysaccharide as a promising immunostimulant. It has been demonstrated to enhance CD4+ activity, thereby promoting immune system functionality.[72] Furthermore, maca polysaccharide possesses notable hepatoprotective properties. Research has revealed its ability to mitigate liver damage induced by cyclophosphamide through modulation of the Keap1-Nrf2 signaling pathway, thereby improving oxidative stress, energy metabolism, and mitochondrial respiration to prevent liver injury.[76] It also alleviates alcohol-induced damage to Hep-G2 cells and significantly enhances levels of superoxide dismutase, glutathione peroxidase, and glutathione S-transferase in mice, indicating its protective capacity

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against alcohol-induced liver damage.[77] Historically, Maca has been used as a natural fertility enhancer. Studies suggest that maca polysaccharides stimulate sperm production, improve sperm quality, and mitigate testicular vasculature damage in azoospermic mice. They inhibit cyst formation and interstitial cell proliferation, facilitate the restoration of the testicular seminiferous epithelium, and safeguard sperm vitality and quantity.[78] Moreover, Maca polysaccharide exerts protective effects against neurodegeneration and oxidative damage in the central and peripheral nervous systems. It enhances glutathione peroxidase activity, reduces malondialdehyde levels, and mitigates hydrogen peroxide-induced cellular injury and reactive oxygen species levels. Additionally, it inhibits cell death, alleviates cell cycle arrest, and reduces caspase-3 and P53 protein expression.[79] In cancer treatment, maca root extract (MRE) activates the NF-κB, STAT1, and STAT3 signaling pathways, reverting tumor-associated macrophages to an M1-like phenotype. Combining MRE with doxorubicin enhances antitumor efficacy, reduces toxicity, and inhibits tumor metastasis by transforming the immunosuppressive tumor microenvironment into an immunostimulatory state through immune system regulation.[80] Maca polysaccharides, when combined with 5-fluorouracil, have been shown to enhance the antitumor efficacy of the latter by modulating CD4, offering a novel approach for cancer treatment.[81] However, the complex structure of Maca polysaccharide and the variability introduced by different extraction methods pose challenges for comprehensive analysis of its biological activity and function.[82] Despite recent advancements, future research must prioritize understanding the relationship between the structure and efficacy of Maca polysaccharides.

With the rising international demand for Maca, the cultivation and processing of this plant have progressively expanded to various regions worldwide. Maca is characterized by its diverse varieties, primarily classified based on the color of its root tuber, with yellow, red, and black being the most common. Among these, black and red Maca are the most prominent branches in the phylogenetic tree, whereas yellow Maca has been relatively less studied. Furthermore, research suggests that Maca exhibits between 13 and 17 distinct phenotypes, each displaying unique variations in morphology and biochemical characteristics, in addition to the three primary colors.[83] The researchers observed significant variations in the levels of sulfated glucoside present in the different varieties of Maca. The occurrence of red, purple, and black Maca is likely influenced by the altitude at which it is cultivated. This, in turn, may result in the induction of specific treatments and health benefits that differ from those initially anticipated.[84] Black Maca oil and its lipid and polysaccharide fractions exhibited greater effectiveness than yellow and red varieties. This finding highlights the limited attention given to other colors, with the exception of black.[85] Researchers employed metabolomic fingerprinting, metabolomic profiling, and genomics to analyze 71 samples of Maca from Peru and China, revealing significant differences in chemical composition and color between the samples from the two countries.[86] The study found that Japanese maca exhibited the highest levels of total purple maca anthocyanins, antioxidant activity, and anthocyanin content. In contrast, the highest levels of purple maca betacyanins were identified in white maca.[16] Research has demonstrated that the concentrations of cadmium (Cd) and lead (Pb) in yellow and purple Maca, originating from both soil and roots, surpass the permissible limits. This finding suggests that Maca phenotypes differ in their capacity to accumulate these metals. Consequently, the color of Maca plays a crucial role in selecting raw materials with low metal content and high quality.[87] In recent years, there has been an increase in research focused on the variation in maca, driven by the application of modern technology to analyze its genome and metabolome. Scientists have aimed to gain a deeper understanding of the biological characteristics of different maca varieties through these analyses. Notably, Zhang and colleagues have reported a high-quality assembly of the maca genome, identifying two closely spaced Maca-specific whole-genome duplications (WGDs). When compared to other members of the nightshade family (Solanaceae), it has been demonstrated that the expansion of the maca gene and gene family is associated with responses to abiotic stress, the transmission of hormonal signals, and the synthesis of secondary metabolites, facilitated by these WGDs.[88] The research team used a protein interaction map to explore how Maca molecules respond to heat stress. Their findings indicate that protein processing in the mitochondrial matrix may be crucial in this mechanism.[89]

Maca, a traditional food and medicinal plant, is recognized as a "superfood" and has recently gained significant popularity in the global health food market.[90] Its nutritional value, including minerals, dietary fiber, and protein, along with beneficial secondary metabolites like Maca polysaccharides, polyphenols, macaenes, and thiodigin, makes it an ideal candidate for functional food development.[91] The expansion of the functional food market has intensified interest in the potential of functional foods to address chronic health conditions such as obesity, cardiovascular disease, and diabetes.[92] Among these, Maca has emerged as a promising functional foodstuff.[93] Research suggests that Maca may offer preventive benefits for disorders related to carbohydrate and lipid metabolism, as well as contribute positively to vascular health.[94] The development of related functional products based on the characteristics of Maca is anticipated to leverage its role of maca in the health industry more effectively and is poised to emerge as a new trend in future research. As previously noted, Maca has been consumed in Peru for thousands of years. Traditionally, it was prepared by boiling and consumed as a staple food. Alternatively, it was made into soup and juice. Currently, it is being transformed into modern dietary supplement in various forms, including tablets, capsules, oral liquids, sweets, beverages, tea, and coffee. Beyond its intrinsic benefits, ensuring quality control in Maca production is of paramount importance. This can be achieved through advanced analytical techniques such as ion chromatography using high-performance liquid chromatography (HPLC), ultrahigh-performance liquid chromatography–photodiode array detection (UHPLC-PDA), and gas chromatography–mass spectrometry (GC-MS).[8,95,96] These methods, which focus on the quality control of Maca's different chemical components, help to ensure its clinical efficacy and safety. To address the current issues surrounding Maca, it is essential to implement rigorous quality control measures and trace the product's origin. Additionally, there is a pressing need for more scientific evidence to support the claims made about Maca-related products on the market. This includes conducting clinical studies to investigate the mechanisms of action of these products.

Despite extensive research on Maca, the precise mechanism of its action remains unclear. Most studies have concentrated on the Maca root, largely due to the traditional non-utilization of its leaves. This focus has resulted in comparatively less attention being given to the leaves. However, recent studies have suggested that Maca leaves possess beneficial properties similar to those of the root, indicating potential avenues for resource optimization. Therefore, future research should not only explore the properties of Maca leaves but also investigate the impact of Maca on diverse populations.[97] Additionally, it should explore the relationship between Maca's constituents and its health benefits. Understanding these aspects will help clarify Maca's potential role in preventing chronic diseases. In terms of genetic research in Maca, large-scale genome-wide association analysis can be carried out internationally by sharing genetic data resources to reveal the genetic basis of Maca's adaptation to different environments. In terms of drug research and development, we cooperate in clinical trials to accelerate the research and development process of Maca-related drugs and improve the efficiency and reliability of research results. To explore the importance and potential impact of international cooperation in promoting the development of Maca research, such as promoting knowledge sharing, integrating research resources, and broadening research horizons. Such studies will contribute to a more comprehensive understanding of Maca's global health impact.

Conclusion

This study employs bibliometric analysis to examine the current state of research on Maca. The findings indicate that the field is currently experiencing a period of heightened activity and prosperity. Our research highlights China as a dominant player in this area, emphasizing the importance of international collaboration in advancing the study of Maca. This collaboration could be further enhanced with other key countries such as Peru, the USA, and Korea. Notably, Maca polysaccharide research emerges as a prominent focus within the field. Future investigations could explore the mechanisms of action and the similarities and differences among various phenotypes of Maca polysaccharide. Additionally, examining the discrepancies and commonalities between studies conducted in different countries would be beneficial. However, our initial search was limited to the Web of Science databases, specifically the SSCI and SCI-E, which may have resulted in the exclusion of some relevant literature due to keyword limitations. A more comprehensive understanding of the literature on Maca is required. Individual results may vary; therefore, future research should utilize a more extensive dataset for a more in-depth analysis.

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Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

Disclosure

The authors report no conflicts of interest for the present paper.

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